Dynamic And Design Sensitivity Analysis
of Rigid and Elastic Mechanical
Systems With Intermittent Motion

Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Methods developed for analysis of intermittent motion, flexible system dynamics, design sensitivity, and differential-algebraic equations are summarized. New techniques for dynamics of multibody flexible systems include mixed vibration and static correction modes. Dynamic design sensitivity analysis methods were developed, using singular value decomposition. Numerical integration methods for mixed differential-algebraic equations developed are based on singular value decomposition and hybrid generalized coordinate partitioning-constraint stabilization. Citations to sixteen published papers/reports are made.

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Intermittent Motion

A reformulation of the logical function method for representing impact events was developed, using a coefficient of restitution parameter to establish a relationship between damping and elastic effects. Both the logical function and pieced interval momentum balance methods for representing intermittent motion effects were coded into the DADS simulation language and tested on a variety of problems. The pieced interval technique demonstrated excellent numerical performance. In addition, the pieced interval method was reformulated to deal with constraint addition and deletion, for analysis of certain classes of mechanisms. Continued development and application for armaments and vehicles was pursued under an exploratory development project.

Flexible System Dynamics

Flexibility effects within planar and three dimensional dynamic systems were represented using a modal coordinate technique to describe deformation of bodies, relative to a body fixed reference frame that is used to locate the body in a global reference frame [1, 2, 3, 4]. A general formulation is employed, to allow the user to obtain normal vibration modes and stiffness and mass matrices from sources such as experiment, finite element analysis, and analytical techniques. With this approach, a broadly applicable formulation has been obtained.

Recently developed theories of static correction mode methods in transient structural dynamics, developed primarily for aerospace and automotive applications, were adapted for inclusion in formulation for geometrically nonlinear system dynamics with flexible bodies [5,6]. Test calculations for dynamics of mechanisms and machines with flexible components were carried out using the theory, formulation, and experimental computer code [7, 8, 9]. Excellent numerical results were obtained using static correction

mode theory from structural mechanics to account for local deformations that are induced by large reaction forces that occur in kinematic joints. Examples treated indicate that superior results can be obtained using the static correction mode theory in conjunction with the more conventional normal modes of vibration of structural components. Two of the examples showed that computing cost for comparable accuracy can be as much as three orders of magnitude lower if static correction modes are used in conjunction with normal modes of vibration, as opposed to using exclusively normal modes of vibration. These results were not totally anticipated, but indicate the value of the approach for future applications to dynamics of high performance robots, vehicles, aircraft, space structures, and other mechanical systems in which forces transmitted by kinematic connection between flexible bodies are important.

Design Sensitivity Analysis

The adjoint variable method for design sensitivity analysis of dynamic systems was extended to the generalized coordinate partitioning formulation, for both first and second order design sensitivity analysis [10, 11]. Test calculations with moderately simple mechanisms showed that accurate derivatives of dynamic response measures with respect to design parameters can be obtained and used for dynamic system optimization. Large amounts of data accumulated during forward integration in time, however, must be stored for backward integration of the adjoint equations. This factor lead to investigation of alternate methods for numerical integration of the equations of motion, to minimize the amount of data that must be stored for implementation of the algorithm.

A numerically efficient adjoint variable design sensitivity analysis formulation was developed, using singular value decomposition for numerical

integration for both state and adjoint equations [12, 13, 14]. Symbolic
computation was employed to generate the many derivatives required with
respect to design variables that are required for design sensitivity analysis,
allowing generality in user definition of parameters to be declared as design
variables. The formulation was implemented with singular value decomposition
and tested on moderate sized examples and demonstrated excellent accuracy
[15].

Numerical Integration of Differential-Algebraic Equations

Development of singular value decomposition for defining an optimized set
of independent generalized coordinates has demonstrated excellent numerical
stability for integration of the equations of motion and adjoint equations for
design sensitivity analysis [12, 13, 14, 15]. In addition to much improved
numerical performance, clear physical insights have been gained into the
nature of composite generalized coordinates that are defined by singular value
decomposition. It is shown that composite generalized coordinates span the
tangent hyperplane to the constraint surface, associated with kinematic
constraints of the system.

A hybrid constraint stabilization-generalized coordinate partitioning
method was developed that demonstrates superior computational efficiency and
stability, as compared to methods used earlier to solve mixed differential-
algebraic equations [16]. Numerical criterion for ill-conditioning of the
constraint Jacobian with respect to dependent generalized coordinates was
developed and implemented, as a positive means for controlling generalized
coordinate selection. Numerical experimentation with challenging test
problems demonstrated that the new hybrid algorithm successfully integrates
mixed differential-algebraic equations that are intractable by prior methods.

List Of Publications

1. Shabana, A.A., and Wehage, R.A., "A Coordinate Reduction Technique for Transient Analysis of Spatial Substructures with Large Angular Rotations," to appear, _Journal of Structural Mechanics_, Vol. 11, No. 3, 1983, pp. 401-431.

2. Shabana, A.A., and Wehage, R.A., "Spatial Transient Analysis of Inertia-Variant Flexible Mechanical Systems," submitted to _Journal of Mechanisms, Transmissions, and Automation in Design_, Vol. 105, No. 3, 1983, pp. 371-378.

3. Kim, S.S., Shabana, A.A., and Haug, E.J., "Vehicle Dynamics with Flexible Components", _Proceedings First U.S. Army Conference on Applied Mathematics and Computing_, May 1983.

4. Kim, S.S., Shabana, A.A., and Haug, E.J., "Automated Vehicle Dynamic Analysis with Flexible Components", _Journal Of Mechanisms, Transmissions, and Automation in Design_, Vol. 105, No. 1, 1984, pp. 126-132.

5. Yoo, W.S., _Dynamics of Flexible Mechanical Systems using Finite Element Lumped Mass Approximation and Static Correction Modes_, Ph.D. Thesis, The University of Iowa, Nov., 1984.

6. Yoo, W.S., and Haug, E.J., "Dynamics of Articulated Structures, Part I: Theory," _Journal o f Structural Mechanics_, to appear, 1986.

7. Yoo, W.S., and Haug, E.J., "Dynamics of Articulated Structures, Part II: Computer Implementation and Applications," _Journal of Structural Mechanics_, to appear, 1986.

8. Yoo, W.S. and Haug. E.J., "Dynamics of Flexible Mechanical Systems Using Vibration and Static Correction Modes," _Journal of Mechanisms, Transmissions, and Automation in Design_, to appear, 1986.

9. Yoo, W.S. and Haug, E.J. "Dynamics of Flexible Mechanical Systems," _Proceedings, Third Army Conference on Applied Mathematics and Computing_, May 1985.

10. Haug, E.J., and Ehle, P.E., "Second Order Design Sensitivity Analysis of Mechanical System Dynamics," _Int. J. Num. Meth. Engr._, Vol. 18, 1982, pp. 1699-1717.

11. Haug, E.J., Mani, N.E., and Krishnaswami, P., "Design Sensitivity Analysis and Optimization of Dynamically Driven Systems", _Computer Aided Analysis and Optimization of Mechanical System Dynamics_, Springer-Verlag, Heidelberg, 1984, pp. 555-636.

12. Mani, N.K., Haug, E.J., and Atkinson, K.E., "Applications of Singular Value of Decomposition for Analysis of Mechanical System Dynamics," _Journal of Mechanisms, Transmissions, and Automation in Design_, Vol. 107, No. 1, 1985, pp. 82-87.

13. Mani, Neel K. and Haug, Edward J., "Singular Value Decomposition for Solution of Differential-Algebraic Equations of Mechanical System Dynamics," _Proceedings of Second Army Conference on Applied Mathematics and Computation_, June 1984.

14. Mani, N.K., _Use of Singular Value Decompostion for Analysis and Optimization of Mechanical System Dynamics_, Ph.D. Thesis, The University of Iowa, August 1984.

15. Mani, N.K., and Haug, E.J. "Singular Value Decomposition for Dynamic System Design Sensitivity Analysis," _Engineering with Computers_, to appear, 1985.

16. Park, T.W. and Haug, E.J., "A Hybrid Constraint Stabilization-Generalized Coordinate Partitioning Method for Machine Dynamic Simulation," _Journal of Mechanisms, Transmissions, and Automation in Design_, to appear, 1986.

List Of Scientific Personnel Supported

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